OVERVIEW OF SOIL EROSION FROM IRRIGATION[a]

By Paul K. Koluvek,[1] Kenneth K. Tanji,[2] and Thomas J. Trout,[3] Members, ASCE

ABSTRACT: Of the 15,000,000 ha (37,000,000 acres) of irrigated land in the U.S., 21% is affected by soil erosion to some extent. Irrigation-induced soil erosion has been studied, primarily in the Northwestern United States, since 1940. A number of studies have measured annual sediment yields from furrow-irrigated fields exceeding 20 t/ha (9 tons/acre) with some fields exceeding 100 t/ha (45 tons/acre). Under the center-pivot sprinkler method, sediment yields as high as 33 t/ha (15 tons/acre) have been measured. Annual sediment yields as high as 4.5 t/ha (2 tons/acre) were measured from irrigation tracts. Erosion is seldom excessive on slopes less than 1% and is often excessive on slopes greater than 2%. Erosion reduces the agricultural productivity of the fields and causes off-farm damages. In southern Idaho, crop yield potential has been reduced by 25% due to 80 years of irrigation-induced erosion. Some irrigation districts spend more than $50,000 annually to remove sediment from drains. Sediment in irrigation return flows causes major water-quality degredation problems in several rivers in the Western United States.

INTRODUCTION

In the United States, erosion resulting from rainfall on cropland has been considered a major problem for many years. In *The 1977 National Resource Inventory* (1978), the U.S. Department of Agriculture estimated that as much as 3.6 billion t (4.0 billion tons) of sediment are produced annually. About half of that total [1.7 billion t (1.9 billion tons)] is eroded from cropland. These estimates were based on samplings across the country using the universal soil loss equation (USLE). No estimates are available for total erosion or sediment yield from irrigated cropland because no method was available for estimating erosion or sediment yield caused by irrigation at the time of the inventory.

In 1985 and 1986, the USDA Soil Conservation Service (SCS) conducted surveys to estimate the areal extent of irrigation-induced erosion problems. The surveys estimated that in 37 states, 3,200,000 ha (8,000,000 acres) or 21% of 15,000,000 ha (37,000,000 acres) of irrigated cropland are affected by erosion to some degree. Fig. 1 shows the general location of irrigated lands affected by erosion in the 12 western states. Table 1 gives the estimated acreage of affected area and percent, by method of irrigation, for those states.

The present paper reviews studies carried out over the past 50 years of erosion and sediment yield from irrigated cropland. All but one of these studies deal with furrow irrigation. The studies indicate the extent of irri-

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[a]Presented at the August 4–6, 1986, ASCE Water Forum held at Long Beach, CA.

[1]Irrig. Engr., WNTC, USDA-Soil Conservation Service, 511 N.W. Broadway, Portland, OR 97209-3486.

[2]Prof. of Water Sci., Dept. of Land, Air and Water Resour., Univ. of California, Davis, Davis, CA 95616.

[3]Agric. Engr., USDA Agric. Res. Service, Kimberly, ID 83301.

Note. Discussion open until May 1, 1994. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on May 26, 1992. This paper is part of the ***Journal of Irrigation and Drainage Engineering***, Vol. 119, No. 6, November/December, 1993. ©ASCE, ISSN 0733-9437/93/0006-0929/$1.00 + $.15 per page. Paper No. 4141.

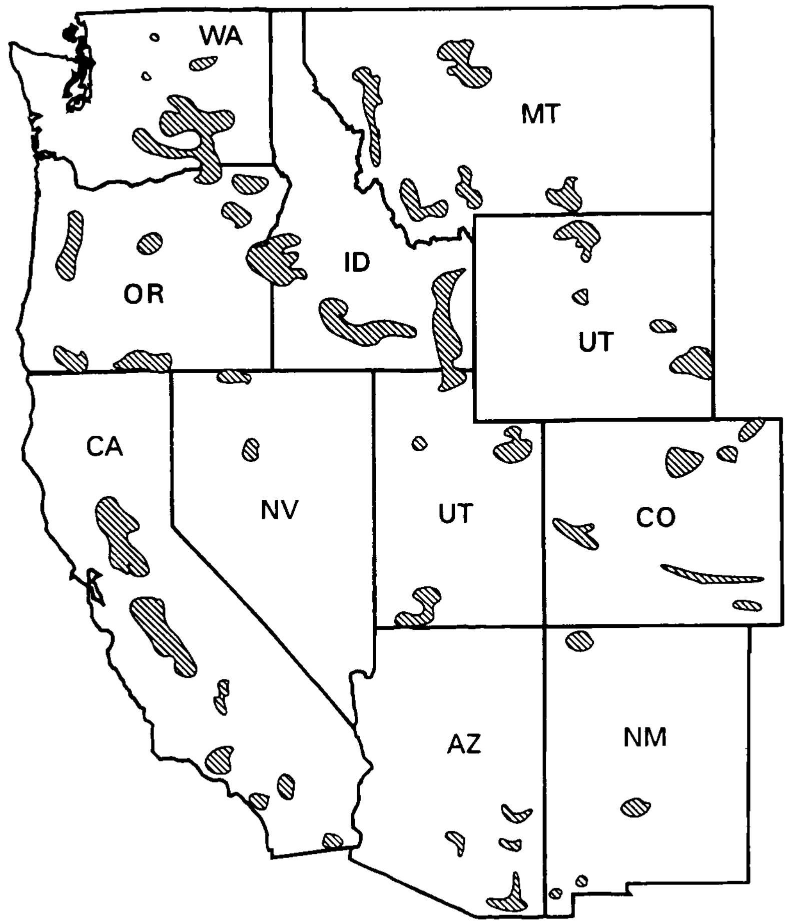

FIG. 1. Areas of Irrigated Land Affected by Erosion in 12 Western States

gation-induced erosion and the resulting soil productivity loss and sedimentation damage. The present paper provides background information for the three other papers in this series on erosion and sedimentation from irrigated land (Trout and Neibling 1993; Carter et al. 1993; Carter 1993).

Irrigation Methods

Irrigation water is applied by four basic methods: (1) surface; (2) sprinkler; (3) trickle; and (4) subsurface. Erosion is not a concern with the last two methods because there generally is no overland flow to convey the sediments.

With surface application methods, water is applied directly to the soil surface either by controlled flooding of borders and basins or in small channels called furrows or corrugations. Most erosion caused by surface irrigation occurs with the channelized flows in furrows.

With the sprinkler method, water is sprayed into the air through a sprin-

TABLE 1. Estimate of Area of Irrigated Land Affected by Erosion in 12 Western States

State (1)	Total Area Affected by Erosion[a] ha (2)	acre (3)	Percent, by Method of Irrigation Border (4)	Furrow (5)	Sprinkler (6)	Other[b] (7)
Arizona	72,800	180,000	n/a[c]	n/a[c]	n/a[c]	n/a[c]
California	510,000	1,260,500	40	36	20	4
Colorado	384,400	950,000	15	45	30	10
Hawaii	40	100	0	20	15	65
Idaho	343,200	848,000	1	69	30	0
Montana	69,600	172,000	5	30	10	20
Nevada	2,000	5,000	15	75	10	0
New Mexico	5,300	13,000	0	0	77	23
Oregon	103,700	256,300	4	17	46	33
Utah	20,600	51,000	2	47	3	48
Washington	448,000	1,109,000	0	42	58	0
Wyoming	80,000	200,000	1	90	2	7
[Total]	2,041,440	5,044,900	—	—	—	—

[a]Total irrigated land = 10.5 million ha (26.1 million acres).
[b]Includes wild flooding, contour ditch, and trickle irrigation.
[c]Not available.

kler nozzle and falls on the land surface like rain. Erosion can occur when the application rate exceeds the soil infiltration rate, causing surface runoff. This occurs most commonly with center-pivot sprinkler systems.

Erosion and Sedimentation Processes

Erosion and sedimentation by water involves the detachment, movement, and deposition of soil particles. The two primary processes are the detachment and/or picking up of particles (erosion) and the transport of particles with the flow. Both processes depend on both soil and hydraulic properties: the erodibility of the soil and erosivity of the flow, and the transportability of the sediments and transport capacity of the flow.

Under surface-irrigated conditions, erosion is caused by water flowing over soil, most commonly as concentrated flow in furrows. Furrows erode similar to large rills or small gullies that occur under rainfall conditions. Sprinkler waterdrops, like raindrops, dislodge soil as they impact the soil surface. If the application rate exceeds the soil infiltration rate, water ponds on the surface until it begins to flow downslope. The flow transports sediment initially in thin sheets, and as the flows concentrate, in rills and gullies. This erosion process is similar to that caused by rainfall except that only a small portion of an area is sprinkled at any time. Trout and Neibling (1993) describe erosion and sedimentation processes under surface and sprinkler irrigation in detail.

Measurement and Data Interpretation

Measurements are most commonly made of the sediment carried by the water past some point—usually the tail end of a furrow or field or the wastewater outflow point(s) from an irrigation system. The measurement point chosen is usually determined by the damage being assessed–soil and productivity loss from a field or sedimentation of drains and rivers. Measurements are generally of sediment concentration and water flow rate or volume, the product of which gives sediment loss or yield in terms of mass per unit area per unit time.

It is often difficult to know which process—erosion or transport capacity—is controlling the sediment movement in a channel. The erosion process will generally limit transport over short distances or when flow rates in channels continually increase with downstream distance, as under rainfall or sprinkler-irrigation conditions. The transport capacity often limits transport in long channels especially where flow rates decrease with distance as in furrows.

Knowing which process dominates is critical to evaluating and interpreting erosion data. If the erosion process is most important, then the upstream conditions of slope, flow rate, furrow length, and soil erodibility are critical factors. If the transport capacity limits transport, then the flow conditions at the measurement point and sediment particle sizes and densities are important. Measurements of sediment outflow from long irrigation furrows in erodible soils probably indicate the transport capacity of flow at that point rather than erodibility of the soil. The measurement quantifies sediment carried to the drains but probably underestimates erosion damage on the field since much of the sediment eroded from the head end of the field likely deposited in the tail reach of the furrow where flow rates are small.

EROSION STUDIES PRIOR TO 1965

The first known reference to erosion caused by irrigation was presented in an irrigation text by Israelson (1932), who stated that ". . . it is rather difficult to avoid harmful soil erosion when water is applied to cereals before the plants are large enough to add stability to the soil. The young tender plants are easily killed by a slight amount of soil erosion that may leave no permanent determined effect on the land."

Taylor (1935) discussed the influence of tillage on furrow erosion in orchards. The author stated ". . . loose, cultivated soil is much more easily picked up and carried away." This is the first known study that discusses ways to minimize the erosion problem by using permanently vegetated furrows and, where the soil is disturbed by cultivation, spreading bean straw or hay to reduce water velocity.

Taylor (1940) is the first published study of the erosion process in furrow irrigation. In this study, an attempt was made to relate the laboratory studies of Gilbert (1914) to furrow erosion. The study identified slope, flow rate, and particle-size distribution as important parameters in the erosion process, and provided the following management concepts to minimize erosion (Taylor 1940):

1. Slope along the furrow should be kept to a minimum
2. Furrow shape should be shallow and smooth
3. Excessive pulverization of the soil should be avoided

The earliest known attempt to measure erosion in the field was in 1937 by the U.S. Department of Agriculture (USDA), Soil Conservation Service (SCS), near Ellinsburg, Wash. Soil losses of 67–134 t/ha (30–60 tons/acre) were measured from furrow-irrigated potatoes (Mech and Smith 1967). The soil textures in this area are predominantly silt loams.

About 1939, the USDA Soil Conservation Office of Research initiated two cooperative studies on erosion in furrow irrigation. These studies were conducted in cooperation with the Utah and Washington Agricultural Experiment Stations.

Utah Study

The Utah study (Israelson et al. 1946) was conducted on silty-clay-loam, loamy-sand, and sandy-loam soils. The study measured soil erosion as mass of soil eroded per unit time. This unit of measurement was based on an erosion equation suggested by Willard Gardner in 1938 (Israelson et al. 1946), which was given as:

$$E = kS^aQ^b \qquad (1)$$

where E = erosion rate; S = furrow slope; Q = flow rate at the measurement point; a and b = empirical exponents indicating the influence of S and Q on the erosiveness of the flow; and k = a unit-dependent coefficient indicating the erodibility of the soil. Gardner assumed that b = 1. This is the first published equation used to predict furrow erosion.

A selection of the measured data are presented in Table 2. The most significant conclusions from this study were:

- Slopes of 2% or greater are excessive and cause harmful erosion when furrow flow rates are 38 L/min (10 gal/min) or greater
- Doubling the furrow slope or flow rate more than doubled the erosion, indicating both a and b in (1) are greater than 1
- Erosion on a given furrow slope is dependent on the stream size and length of the furrow.

Out of the studies came two significant management guidelines. First, the irrigator should improve control of irrigation water by using underground pressurized pipelines. Second, farmers should not use excessive flows.

Israelson et al. (1946) noted, on many occasions, eroded depths of 25–100 mm (1–4 in.) near the head ditches after the first irrigation of sugar

TABLE 2. Measured Soil Erosion in Utah (from Israelson et al. 1946)

Furrow Length		Slope	FLOW RATE				Soil Eroded per Hour	
			Inlet		Outlet			
m (1)	ft (2)	(%) (3)	L/min (4)	gal/min (5)	L/min (6)	gal/min (7)	kg (8)	lb (9)
(*a*) Silty Clay Loam								
73	240	0.59	40	10	20.4	5.4	2.4	5.4
73	240	0.59	114	30	77.6	20.5	16.8	37.0
73	240	2.88	38	10	21.2	5.6	53.6	118.1
73	240	2.88	114	30	101.4	26.8	87.2	192.3
(*b*) Sandy Loam								
61	200	0.35	57	15	8.7	2.3	0.2	0.4
61	200	0.35	114	30	66.6	17.6	19.9	43.8
61	200	6.07	57	15	38.6	10.2	219.5	484.0
61	200	6.07	114	30	98.4	26.0	821.4	1,811.0

beets. At the lower end of the fields, furrows were completely filled with sediment.

Washington Study

The Washington study was designed to determine how to apply sufficient furrow irrigation water for maximum crop production with the least amount of soil and water losses (Mech 1949). Soil loss was measured from several crops on two slopes on a fine sandy-loam soil. This study evaluated the effects of slope and furrow length on furrow erosion and viewed erosion as soil translocation along a furrow.

The Washington study measured the erosion rate for different flow rates as influenced by crop and slope and described the effect of the decreasing flow rate along a furrow on erosion. The relationship between furrow outflow (tailwater runoff) rates and soil loss for row crops and alfalfa on 2% and 7% slopes are shown in Fig. 2. The row crop data are the average for corn and potatoes, which were similar. Fig. 2 shows that erosion is higher for row crops than for close-growing alfalfa and for newly planted than for established alfalfa. The data also indicate soil loss is roughly proportional to outflow rate (i.e. $b = 1$). S. J. Mech in an unpublished work in 1957 predicted that the seasonal erosion amount could be estimated for a furrow section from the flow rate.

Mech (1949) recognized that soil loss measurements at the tail end of the field were not a good measure of erosion on the field. Table 3 shows how flow rates and net erosion decreases along an irrigation furrow.

Some of the important conclusions of this study were (Mech and Smith 1967): (1) A field with two 100 m (300 ft) lengths of run will have less erosion than one 200 m (600 ft) length of run; (2) Generally, furrow-irrigated land with slopes of 2% or greater have an erosion problem; (3) Excessive applications of water greatly increase runoff, which results in more soil being carried from the field and increased sedimentation problems; (4) Soil is most

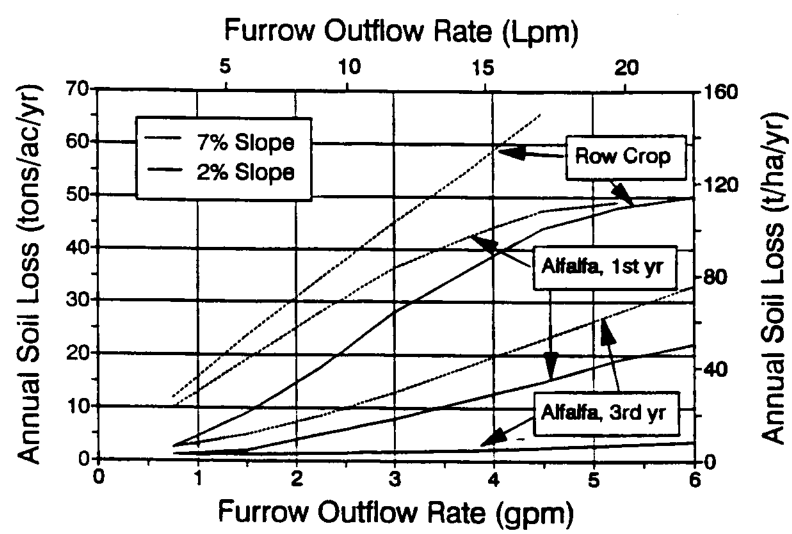

FIG. 2. Relationship between Furrow Outflow Rate and Erosion for Two Slopes (from Mech 1949)

TABLE 3. Measured Flow and Sediment Movement along Furrows during One Irrigation in Washington (from Mech 1949)

Distance from Upper End		Flow Rate per Furrow		Soil Movement per Furrow	
m (1)	ft (2)	L/m (3)	gal/min (4)	kg (5)	lb (6)
0	0	26.6	7.0	0	0
91	300	17.0	4.5	43.3	116
183	600	7.3	1.9	4.8	13
274	900	2.5	0.7	0.4	1

TABLE 4. Measured Soil Loss from 87 m (287 ft) Long Furrow Sections with Varying Slopes and Inflow Rates in North Dakota (from Evans and Jensen 1952)

		SOIL LOSS DURING FIRST HOUR OF IRRIGATION SLOPE					
Inflow Rate		1%		2%		3 1/2%	
L/min (1)	gal/min (2)	t/ha (3)	tons/acre (4)	t/ha (5)	tons/acre (6)	t/ha (7)	tons/acre (8)
23	6	0.0	0.0	0.3	0.10	5.7	2.5
45	12	0.4	0.2	8.3	3.7	21.2	9.5
68	18	1.7	0.8	14.1	6.3	37.3	16.6

susceptible to erosion after seedbed preparation and other tillage operations—therefore, minimize the number of cultivations to reduce soil loss; (5) Each irrigation adds to the total soil loss.

North Dakota Study

A study conducted in North Dakota (Evans and Jensen 1952) measured erosion from 87 m (286 ft) long furrows constructed in various directions on a field to create a range of furrow slopes. The intent was to duplicate conditions at the head end of furrows realizing that is where the greatest erosion occurs. Soil loss was measured over the first hour of irrigation since, according to the authors, the erosion rate decreases during the first hour. Evans and Jensen (1952) fitted their data, summarized in Table 4, to (1) with $a = 2.3$ and $b = 1.5$. They also provided the following guidelines for irrigated furrows:

- Slopes over 2% should be avoided, especially if the length of runs are long, requiring large flow rates
- On steep land, furrows can be oriented on a contour gradient on slopes of 1% or less
- Where it is necessary to use furrows on steep slopes, erosion can be minimized by using short furrow lengths to allow use of small flow rates

Maximum Nonerosive Flow Rate

In 1951, W. D. Criddle (unpublished), developed a relationship for critical or maximum allowable, nonerosive, furrow flow rate Q_m, for various slopes using data from 60 irrigation trials in locations throughout the Western

United States. In 1952, this relationship was refined and resulted in the following equation, first published as a graph in Lawrence (1953):

$$Q_m = 10/S \qquad (2a)$$

with Q_m in gal/min and S in %. And subsequently

$$Q_m = 38/S \qquad (2b)$$

with Q_m in L/min. Eq. (2) provided the first known guide for determining the maximum nonerosive flow rate for a given slope and has been widely used in designing furrow irrigation systems.

Hamad and Stringham (1978) reanalyzed Criddle's data using a more general critical slope-flow rate equation originally suggested by Gardner and Lauritzen (1946).

$$Q_m = cS^d \qquad (3)$$

where c and d = empirical coefficients. Note that when $c = 10$ and $d = -1$, (3) is equivalent to (2a). Table 5 lists their derived coefficients for six soil-type groupings. They conclude that (2) underestimates Q_m at slopes greater than 1%.

RECENT EROSION AND SEDIMENTATION STUDIES

In the late 1960s, the pollution aspects of irrigation return flows became a concern (*Characteristics* 1969). The Water Quality Act Amendments of 1972, better known as PL 92-500, designated irrigation return flows as point-source discharge requiring discharge permits. This stimulated great interest and concern among irrigators and irrigation entities. Interest in the quality of irrigation return flows prompted the U.S. Environmental Protection Agency (EPA) to fund several studies addressing the problem. Most of the studies of irrigation-related erosion and sedimentation were conducted in Idaho, Washington, and California. The USDA Agricultural Research Service (ARS), together with Idaho, Washington, and Wyoming Soil Conservation Service (SCS) funded additional studies.

TABLE 5. Coefficients of Nonerosive Flow Rate Equation (3) Based on Criddle's Data (from Hamad and Stringham 1978)

SOIL DESCRIPTION								
		Subsoil and substratum permeability rate	Depth to Impermeable Layer		c			
Group (1)	Texture (2)	(3)	mm (4)	in. (5)	Q_m L/m (6)	Q_m gal/min (7)	d (8)	Correlation coefficient (9)
I	Heavy	Slow	>914	>36	53.5	14.1	−0.94	0.89
II	Moderately heavy	Moderately slow	508–914	20–36	59.3	15.7	−0.55	0.72
III	Medium	Slow	508–914	20–36	36.8	9.7	−0.73	0.80
IV	Medium	Moderately slow	254–508	10–20	38.6	10.2	−0.70	0.73
V	Light	Moderately permeable	254–508	10–20	66.7	17.6	−0.62	0.73
VI	Very light	Moderately rapid	254	<10	39.9	10.5	−0.55	0.92

Idaho Studies

A 1981 erosion study and a 1982 sediment study for the Middle Snake River Basin estimated that 21% of the 371,000 ha (917,000 acres) of irrigated land had erosion rates greater than established *T* values. The *T* value is defined as the gross annual erosion rate that can be tolerated and still maintain crop productivity. The values used by SCS range from 2 to 11 $t \cdot ha^{-1} \cdot yr^{-1}$ (1 to 5 tons/acre/yr) (Logan 1977). It was estimated that the study area produced more than 2,400,000 t (2,600,000 tons) of eroded soil annually. The studies estimated that 635,000 t/yr (700,000 tons/yr) were leaving the basin and reaching Brownlee and other reservoirs on the Snake River. Of this sediment load, approximately 55% originated from irrigated cropland, 15% from nonirrigated cropland, and 30% from range and forest land. Not all of the irrigated cropland sediment results from irrigation; some results from winter precipitation. In a similar cooperative erosion study for the Upper Snake River Basin, it was estimated that over 18% of the 1,100,000 ha (2,800,000 acres) of irrigated cropland were affected by erosion rates greater than established *T* values.

The USDA Agricultural Research Service at Kimberly, Idaho has conducted extensive erosion studies in Idaho. Brown et al. (1974) measured sediment discharge on two large irrigated tracts in south-central Idaho. The Northside Irrigation District, which irrigates 65,000 ha (160,000 acres) had a net annual sediment loss from farm fields of 254,000 t (280,000 tons) or 4 t/ha (1.8 tons/acre). For this tract, approximately 295,000 t (325,000 tons) were mechanically removed annually from the relatively flat canals and from drains that carried 6% of the diverted water back to the river. Thus, the overall district actually had an annual sediment gain of 45,000 t (50,000 tons).

In the Twin Falls Irrigation District [82,000 ha (203,000 acres)], there was an annual net loss of 38,000 t (42,000 tons), and 78,000 t (86,000 tons) were removed mechanically from drains and canals resulting in a net loss from the fields of 1.3 t/ha (0.6 tons/acre). The soils in the Twin Falls tract, are moderately deep, uniformly textured, silt loams extensively underlain by a lime and silica-cemented hardpan that begins 30–40 cm (12–15 in.) below the surface. In the Northside tract, some of the same soils are found, but at least half of the soils are shallow fine sandy loams or sands.

A recent water-quality monitoring study conducted by the University of Idaho measured sediment and nutrients from 19 irrigation-return-flow areas into the middle Snake River in south-central Idaho (Brockway and Robison 1992). These measurements showed a total of 19,000 t (21,000 tons) of sediment entering the river from 38,000 ha (94,000 acres) of irrigated watersheds between June 1990 and July 1991. This constitutes 0.5 t/ha (0.22 tons/acre) of sediment during the year, essentially all of which was derived from irrigation return flows. Sediment in irrigation return flows has been identified as a major cause of serious sedimentation and water-quality problems in the middle Snake River.

In 1978 and 1979, an extensive field study was conducted by ARS in the Twin Falls, Idaho, area, where sediment yield was measured from 49 fields (Berg and Carter 1980). Examples of some of the sediment data are presented in Table 6. These data show severe sediment losses on fields in row crops with slopes greater than 1%. Close-growing crops show little or no soil loss. Alfalfa actually removed sediment from the irrigation water. One sugar beet field on a 4% slope had an annual sediment loss of 141 t/ha (63

TABLE 6. Annual Sediment Losses for Various Crops in Southern Idaho (from Berg and Carter 1980)

Crop (1)	Furrow Length m (2)	Furrow Length ft (3)	Slope (%) (4)	FLOW RATE Inlet L/min (5)	FLOW RATE Inlet gal/min (6)	FLOW RATE Outlet L/min (7)	FLOW RATE Outlet gal/min (8)	Annual Sediment Loss t/ha (9)	Annual Sediment Loss tons/acre (10)
Corn	190	640	2.5	24.0	6.3	10.2	2.7	37.0	16.5
Cereal grain	220	720	3.0	16.3	4.3	3.4	0.9	4.5	2.0
Beans	280	700	3.0	14.2	3.9	8.1	2.1	56.9	25.4
Sugar beets	210	700	4.0	17.8	4.7	9.5	2.5	141.0	63.0
Peas	190	630	1.5	22.3	5.9	8.7	2.3	11.9	5.3
Alfalfa	150	510	1.0	29.5	7.8	11.0	2.9	0.0	0.0

TABLE 7. Sediment Concentrations Associated with Convex Furrow Ends in Last 5–30 m (15–100 ft) of the Field (Carter and Berg 1983)

FLOW RATE Furrow Inlet L/min (1)	FLOW RATE Furrow Inlet gal/min (2)	FLOW RATE Furrow Outlet L/min (3)	FLOW RATE Furrow Outlet gal/min (4)	Sediment Concentration Inlet (mg/L) (5)	Sediment Concentration Upstream of convex end (mg/L) (6)	Sediment Concentration Outlet (mg/L) (7)
43.5	11.5	22.2	5.9	97	2,460	5,180
38.2	10.1	16.9	4.5	142	4,940	10,600
17.1	4.5	12.8	3.4	123	5,440	13,300
20.8	5.5	2.3	0.6	66	6,310	13,900

tons/acre), which translated to an equivalent depth of 8 to 10 mm (0.3 to 0.4 in.) over the entire field.

Kemper et al. (1985) analyzed recent field data collected in southern Idaho plus several previously published furrow erosion data sets and concluded that the slope exponent a in (1) varies from 1.4 to 2.7 and the flow rate exponent b varies from 1.0 to 1.8, and that erosion is about 50% more sensitive to changes in slope than flow rate (i.e. $a/b \approx 1.5$). They measured decreasing sediment loss rates with time from furrows and attributed part of the initial high erosion rate to the breakdown of dry aggregates on the furrow perimeter when they are wetted quickly by the advancing flow. Brown et al. (1987) also quantified the soil water tension that develops at the furrow perimeter as a result of a low permeability depositional surface seal and hypothesized that this tension stabilizes the perimeter and holds deposited sediments in place.

In the Northwestern United States, it is a common practice to create a tailwater conveyance ditch 15 cm (6 in.) or more deeper than the tail ends of the furrows to ensure water does not pond at the end of the field. This practice increases the water velocity at the lower ends of the furrows, which increases erosion and transport capacity. The resulting steep tail end increases flow velocity and erosion. Increases in sediment load for some fields due to these convex ends are shown in Table 7 (Carter and Berg 1983).

Erosion on irrigated land can have an adverse effect on soil productivity.

Studies by ARS in Idaho (Carter et al. 1985) have shown dramatic reductions in crop yields. As an example, the average wheat yield decreased 50% as topsoil depths decreased from 38 to 13 cm (15 to 5 in.), a yield decrease of 2% per cm (5% per in.) of soil. Sweet corn yields had similar decreases; whereas, barley, dry beans, and alfalfa yields were not as severely affected. Sugar-beet yields were the least affected by topsoil loss. Carter et al. (1985) estimated that the productivity of the soils in south-central Idaho had decreased 25% as a result of irrigation induced erosion over the preceding 80 years.

Washington Studies

The Yakima River Basin in south-central Washington is devoted almost entirely to irrigated agriculture. In the lower 130 km (80 mi) of the basin, irrigation return flows make up nearly the entire summer flow in the river. Carlile (1972) reported that sediment pollution was becoming an increasing problem in downstream diversion canals and in the Yakima River. He stated that canals were receiving irrigation return flows that carried such heavy sediment loads that untreated water was considered almost unsuitable even for irrigation. Because of this problem, many farmers were reluctant to convert from furrow to sprinkler or trickle irrigation. He stated that conversion to sprinkler or trickle irrigation would be a major step in the control of erosion.

A cooperative Yakima River Basin study in the mid 1970s (Soil Conservation Service, unpublished) estimated that 3,300,000 t (3,600,000 tons) of soil is eroded annually on 220,000 ha (544,000 acres) of irrigated land [15 t/ha (6.6 tons/acre)]. 60% of this eroded sediment [8.6 t/ha (3.9 tons/acre)] was estimated to have left the field. The resulting economic consequences include loss of production, cost for extra fertilizer to compensate for lost nutrients, and damages suffered by downstream municipal and industrial water users. Benton County, Wash., located in the lower region of the Yakima Valley, spent about $50,000 a year to remove sediment from road ditches and bridge approaches (Carlile 1972). Other sedimentation costs reported included $65,000 per year in the Sulphur Creek drainage and $50,000 per year in the Yakima-Tieton irrigation district to remove sediment from canals and drains.

King et al. (1982) measured sediment losses from a 800 ha (1,980 acre) irrigated tract in block 86 of Royal Slope in the Columbia Basin west of Othello, Wash. Soil losses over a two-year period from this tract are shown in Table 8. An average of 4.4 $t \cdot ha^{-1} \cdot yr^{-1}$ (1.9 tons/acre/yr) of sediment left the fields. Soil losses from a number of fields with different crops are shown in Table 9. There is a general relationship between slope and soil loss for these fields.

TABLE 8. Annual Sediment Losses from 800 ha (1,980 Acre) Royal Slope Irrigation Tract, Washington (King et al. 1982)

	WATER				SEDIMENT							
	Diverted		Discharged		Diverted		Discharged		Net Loss			
Year (1)	ha-m (2)	acre-ft (3)	ha-m (4)	acre-ft (5)	t (6)	tons (7)	t (8)	tons (9)	t (10)	tons (11)	t/ha (12)	tons/acre (13)
1977	1,081	533	551	271	481	530	4,867	5,365	4,386	4,835	5.5	2.4
1978	1,023	505	530	262	429	473	2,985	3,290	2,556	2,817	3.2	1.4

TABLE 9. Annual Sediment Losses by Crop and Slope from Royal Slope, Wash., Fields (from King et al. 1982)

Field number (1)	Crop (2)	Slope (3)	Sediment Loss t/ha (4)	Sediment Loss tons/acre (5)
1	Corn	1.4	6.3	2.8
2	Corn	1.5	2.9	1.3
3	Corn	2.5	18.0	8.0
4	Corn	3.0	21.4	9.5
5	Beans	1.5	5.4	2.4
6	Beans	3.1	50.5	22.5
7	Beans	3.3	13.8	6.2
8	Winter wheat	1.0	0.2	0.1
9	Winter wheat	2.1	0.8	0.4
10	Winter wheat	3.4	3.5	1.6
11	Winter wheat	4.3	3.1	1.4
12	Spring wheat	3.3	11.6	5.2

TABLE 10. Soil Loss per Irrigation for Various Soil Textures and Furrow Type and Condition in Wyoming (from Fornstrom and Borrelli 1985)

	Length		Slope	Inflow Rate		Recent	SOIL LOSS PER IRRIGATION			
							Wheel Compacted		Nonwheel (Soft)	
Soil texture (1)	m (2)	ft (3)	(%) (4)	L/m (5)	gal/min (6)	cultivation (7)	t/ha (8)	tons/acre (9)	t/ha (10	tons/acre (11)
Light clay	244	800	0.56	72.7	19.2	Yes	6.61	2.95	6.95	3.10
Light clay	244	800	0.56	65.5	17.3	No	4.12	1.84	2.91	1.30
Silty clay	122	400	1.99	41.6	11.0	Yes	16.12	7.19	15.44	6.39
Silty clay	122	400	1.99	41.6	11.0	No	5.90	2.63	5.94	2.65
Clay loam	130	425	2.90	17.0	4.5	Yes	14.48	6.46	2.47	1.10
Clay loam	130	425	2.90	21.6	5.7	No	10.60	4.73	5.22	2.33
Silty loam	269	882	1.97	21.6	5.7	Yes	6.97	3.11	10.56	4.71
Silty loam	269	882	1.97	40.9	10.8	No	21.71	12.36	5.29	2.36
Loam	165	540	0.35	40.9	10.8	Yes	7.55	3.37	0.99	0.44
Loam	165	540	0.35	40.9	10.8	No	1.64	0.73	1.23	0.55
Sandy loam	122	400	2.06	28.0	7.4	Yes	13.37	5.62	6.30	2.81
Sandy loam	122	400	2.06	28.0	7.4	No	3.25	1.45	1.32	0.59

Wyoming Study

Fornstrom and Borrelli (1985) carried out an extensive study in Wyoming that measured soil losses from irrigation furrows in various conditions—recently cultivated and previously irrigated, wheel compacted and uncompacted ("soft" or non-wheel)—in various soil textures; and for various flow rates, lengths of run, and slopes. An example of soil losses from selected sites is presented in Table 10 and average losses for each condition is shown in Table 11. The measurements indicated that greater soil loss can be expected from recently cultivated furrows than from previously irrigated furrows. Soil losses for the first irrigation after cultivation were 60–100% greater than those for previously irrigated furrows. Also, greater soil loss was measured from wheel rows (compacted) than from soft rows (uncompacted). This is probably the result of lower infiltration rates and thus higher outflow rates in the compacted furrows rather than from higher soil erosivity.

TABLE 11. Mean Data for Fields with Two Irrigations, Irrigated in Wheel-Compacted and Nonwheel Rows (from Fornstrom and Borrelli 1985)

Variable (1)	Inflow Rate L/min (2)	Inflow Rate gal/min (3)	Soil Loss per Irrigation t/ha (4)	Soil Loss per Irrigation tons/acre (5)
(a) Furrow Condition				
Cultivated row	28.21	7.61	5.40	2.41
Uncultivated row	29.15	7.70	3.05	1.36
(b) Flow Rate				
Low	23.43	6.19	2.20	0.98
Medium	28.62	7.56	3.70	1.65
High	34.94	9.23	6.79	3.03
(c) Furrow Type				
Wheel compacted	29.00	7.66	4.93	2.20
Nonwheel	29.00	7.66	3.52	1.57
All furrows	29.00	7.66	4.24	1.89

Note: Number of fields = 19; mean furrow length = 180 m (600 ft); mean furrow width = 64 mm (25 in.); mean furrow slope = 2%; and mean soil particle diameter, D_{50} = (79 microns).

Fornstrom and Borrelli (1985) fitted a regression model to their data set. The critical parameters were furrow slope, S (percent), inflow rate, Q_i, mean particle size, D_{50} (μm), and furrow length, L

$$E = \frac{k_1 S^{1.66} Q_i^{2.45}}{D_{50}^{0.47} L^{1.62}} \qquad (4)$$

where E = annual soil loss in $\mathrm{t \cdot ha^{-1} \cdot yr^{-1}}$ (tons/acre/yr) and k_1 is a coefficient equal to 30.9 for metric units ($\mathrm{t \cdot ha^{-1} \cdot yr^{-1}}$, L/min, and m) and 2,460 for English units (tons/acre/yr, gal./min, and ft). This relationship is depicted in Fig. 3.

According to the model, the inflow rate has the greatest influence on soil loss. The mean soil loss for the average field was 3.70 t/ha (1.65 tons/acre) per irrigation when the average flow rate used by the farmer was applied. A flow-rate reduction of 18% reduced the soil loss by 40%. However, an adequate irrigation was not always achieved with a reduced flow rate. A flow-rate increase of 22% increased the soil loss by 80%.

This effect of flow rate represented by the exponent on the Q term in (4), is greater than has been measured in the other studies (Kemper et al. 1985; Evans and Jensen 1952; Mech 1949). This is likely because the study related inflow rate rather than the outflow rate at the sediment measurement point to sediment yield. A small increase in the inflow rate will result in a much larger relative increase in the outflow rate, since infiltration will not change much with inflow. Eq. (4) also predicts that erosion decreases as mean particle size increases. Since the percent of clay-sized particles are known to increase soil aggregate stability and thus reduce erodibility, this result may not be generalizable.

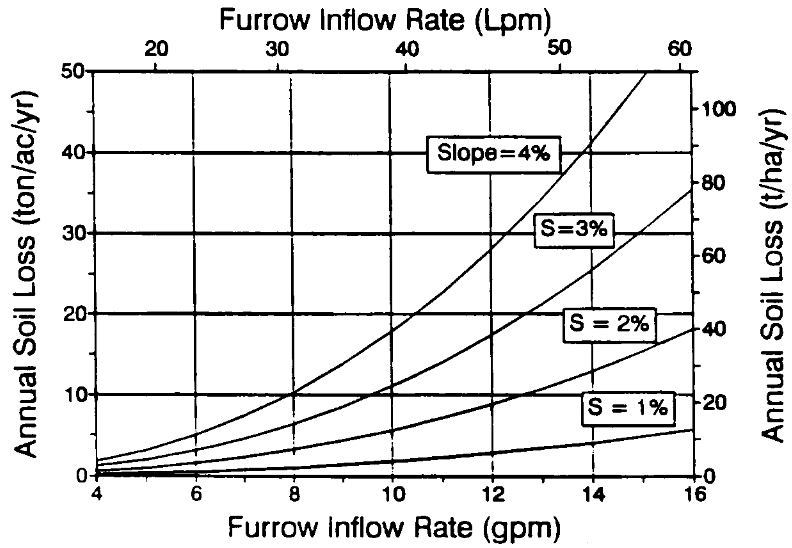

FIG. 3. Predicted Soil Loss per Irrigation as Function of Flow Rate and Slope, for Medium-Textured Soil [D_{50} = 40 μm and Furrow Length of 180 m (600 ft)] (Fornstrom and Borrelli 1985)

California Studies

Most of the irrigated areas in California have small slopes and contain fairly stable soils, resulting in low erosion rates. However, soil erosion and sediment production are still of concern because of the stringent water-quality regulations for discharges into receiving water bodies. Consequently, sediment yield from irrigated areas has been studied.

Colusa Basin Drain

The Colusa Basin Drain (CBD) conveys flood runoffs and irrigation return flows from 400,000 ha (1,000,000 acres) of upland watershed and valley-floor agricultural lands on the west side of the Sacramento Valley. The 110 km (70 mi) Colusa Basin Drain generally discharges between 14 to 85 m^3/s (500 to 3,000 ft^3/s) during the irrigation season. Discharge peaks in excess of 240 m^3/s (8,500 ft^3/s) with substantial bank overflows during the largest storm runoffs.

Water discharge and sediment yield were monitored for the nonirrigation (October–March) and irrigation (April–September) seasons, from 1977–81 (Tanji et al. 1983). During the nonirrigation seasons for the four years of monitoring, 3.2 billion m^3 (2,600,000 acre-ft) of storm water containing 840,000 t (926,000 tons) of suspended solids were discharged. This was equivalent to an annual average discharge of 200 mm (8 in.) of precipitation runoff and 0.52 t/ha (0.23 tons/acre) of sediments from the drainage area. During the irrigation seasons for the 4 years, 1.9 billion m^3 (1,500,000 acre-ft) of irrigation return flows and 170,000 t (190,000 tons) of suspended solids were discharged. This was equivalent to 350 mm/yr (14 in./yr) of return flow and 0.30 t/ha (0.14 tons/acre) of solids annually from 140,000 ha (350,000 acres) of irrigated lands. One analysis showed that nearly half of these solids were organic, probably originating from rice fields. Clearly, more sediments

TABLE 13. Annual Sediment Losses under Center-Pivot Irrigation

Slope (%) (1)	Crop (2)	Annual Sediment Loss t/ha (3)	Annual Sediment Loss tons/acre (4)
3	Winter wheat	6.5	2.9
4	Winter wheat	0.0	0.0
4	Potatoes	15.0	6.7
8	Winter wheat	1.3	0.6
8	Winter wheat	16.1	7.2
13	Winter wheat	32.5	14.5
15	Winter wheat	22.4	10.0
23	Potatoes	33.4	14.9

sprinklers but is common near the outer end of low-pressure center-pivot systems, where application rates generally exceed 50 mm/h (2 in./h) and may exceed 100 m/h (4 in./h) (Kincaid et al. 1990). Table 12 summarizes center-pivot runoff measured in the Columbia basin in Washington and the Snake River plain in Idaho under both conventional and reservoir tillage. Because only a small portion of a field receives high center-pivot application rates at one time, runoff—and thus eroded sediments—are seldom conveyed far from the eroding slope, and off-site impact is usually small.

The only study to date to measure erosion under sprinkler irrigation was carried out under center-pivot systems in 1984 by the SCS (the data is unpublished). The measurements showed that soil losses under center pivots can be significant, especially for row crops, and the amount of erosion increases with increasing slope (Table 13).

SUMMARY AND CONCLUSION

Approximately 21% of the irrigated cropland in the United States is affected by erosion. When silty-textured soils on slopes greater than 1% are furrow irrigated, T values of 2–11 $\mathrm{t \cdot ha^{-1} \cdot yr^{-1}}$ (1–5 tons/acre/yr) are often exceeded. Erosion on irrigated cropland has decreased the crop yield potential in southern Idaho by 25%. Some irrigation districts spend tens of thousands of dollars annually removing sediment from drains and canals. Degradation of receiving rivers and lakes downstream of irrigated areas is becoming a widely recognized and serious problem.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

a, b = empirical exponents, (1);
c, d = empirical coefficient and exponent, (2);
D_{50} = mean soil particle diameter, microns;
E = soil erosion or soil loss in weight per unit area per unit time;
k = empirical constant, (1);
k_1 = empirical constant, (4);
L = furrow length in m (ft);
Q = average outflow stream in L/m (gal/min);
Q_i = inflow stream size in L/m (gal/min);
Q_m = maximum nonerosive stream in Lpm (gal/min); and
S = slope in percent.